The impact of video motion analysis on kinematics graph interpretation skills

Robert J. Beichner
North Carolina State University, Physics Department, Raleigh, North Carolina 27695
(Received 28 July 1995; accepted 4 January 1996)

Video motion analysis software was used by introductory physics students in a variety of instructional settings. 368 high school and college students took part in a study where the effect of graduated variations in the use of a video analysis tool was examined. Post-instruction assessment of student ability to interpret kinematics graphs indicates that graphs using the tool generally performed better than students taught via traditional instruction. The data further establishes that the greater the integration of video analysis into the kinematics curriculum, the larger the educational impact. An additional comparison showed that graph interpretation skills were significantly better when a few traditional labs were simply replaced with video analysis experiments. Hands-on involvement appeared to play a critical role. Limiting student experience with the video analysis technique to a single teacher-led demonstration resulted in no improvement in performance relative to traditional instruction. Offering more extensive demonstrations and carrying them out over an extended period of time proved somewhat effective. The greatest impact came from a combination of demonstrations with hands-on labs. The curricular modifications employed in the different classrooms and the methods used to evaluate them are discussed. © 1996 American Association of Physics Teachers.

I. INTRODUCTION

A. Graph misinterpretations

Research has established\textsuperscript{1-3} that introductory physics students have consistent difficulties with the interpretation of kinematics graphs—i.e., graphs of position, velocity, or acceleration versus time. Probably the most commonly occurring misunderstanding of these graphs is the belief that the graphs are some form of photographic-like replication of the motion event. This "graph as picture" error can manifest itself in a variety of ways. The most obvious example often occurs when students are given a particular situation, say of a bicycle rolling down a hill and over a small bump, and then are asked to sketch a relevant kinematics graph. The resulting drawing often duplicates the physical configuration of the given motion event, right down to the bump at the end of the path. In effect, students create a graph of $y$ vs $x$ instead of $y$ (or another kinematics variable) vs $t$. This error is especially problematic when the horizontal motion is a linear function of time. Projectile motion, for example, has $y$ vs $x$ and $y$ vs $t$ graphs which share the sample parabolic shape, making graph as picture errors hard to detect.

Nearly a quarter of all post-instruction students, perhaps illustrating another aspect of the same error, tend to indicate a graph of identical shape when they are asked to switch from one kinematics graph to another (e.g., from position to velocity or velocity to acceleration).\textsuperscript{3} The belief that kinematics graphs are like photographs of the situation might lead students to the conclusion that the graph's appearance has no reason to change simply because one changes variables on the vertical axis. Preliminary analysis of interview data indicates that this is the case—students comment that they pick identical graphs specifically because they "looked the same."

Another misinterpretation uncovered by research\textsuperscript{4,5} is referred to as slope/height confusion. Asked to indicate the point of maximum (or minimum) slope on a graph, students often pick the place with the largest (or smallest) ordinate value, where the slope is actually zero. Recent research by the author\textsuperscript{7} found other difficulties related to slopes, including the surprising inability to calculate the slope of lines which do not pass through the origin, even though students have few problems determining the slope of lines that do go through $(0,0)$.

One of the most critical difficulties detected in post-instruction students is that most do not understand the meaning of the areas under graphed curves. Further, questions intended to test for this knowledge can be correctly answered by use of a formula, without students recognizing that the calculation is determining an area.\textsuperscript{3}

B. Instructional innovations

Because of the importance of kinematics graphs in the introductory physics course, a wide variety of instructional techniques have been developed to address the difficulties noted above. A hallmark of the very successful\textsuperscript{9} RealTime Physics\textsuperscript{7} and Workshop Physics\textsuperscript{8} curriculum packages is the extensive practice students are given in predicting and examining kinematics graphs. Graphs and Tracks,\textsuperscript{9} one of the most popular pieces of instructional physics software,\textsuperscript{10} is specifically designed to help students better understand kinematics graphs. Another approach has long been advocated by Dean Zollman.\textsuperscript{11} He has students place an acetate transparency on a video screen and step through a motion video one frame at a time, marking the changing positions of objects on the screen. After taking measurements from these marks, his students can then create kinematics graphs which describe the motion. This pedagogical approach has been modified by several groups, including Zollman's,\textsuperscript{11-14} to take advantage of the expanding video capabilities of microcomputers. An earlier study\textsuperscript{15} directly comparing this technique to research done on ultrasonic motion detector laboratories\textsuperscript{16} showed that the video method was not as effective as the sonic microcomputer-based laboratory. That particular investiga-
tion was trying to make as close a comparison between the
two instructional methods as possible—students used video
to examine a single motion event.

This paper describes an attempt to better utilize the power
of the video analysis technique in a variety of instructional
settings, and then measure its impact. There was reason to
believe that embedding the technology into a redesigned
curriculum would improve its effectiveness.

C. Why should video work?

Two special software programs—a video data analysis
tool and a video capture utility—were written for the project.
The basic functionality of the analysis package stems from a
desire to take advantage of the strong response of the human
visual perception system to objects moving in the visual
field. People naturally pay attention to motion and are able to
perceive slight changes in the position of very small objects,
even against complex backgrounds. Studies showing the
effectiveness of interactive video instruction (IVI) illustrate
that this can be used to advantage in educational settings.

A very complicated web of nerve cells in the retina provides
a great deal of information processing before the signals ever leave the eye. These initial stages of image analysis
do not share general mental resources like memory and
attention. Because of this they are cognitively impenetrable and are not greatly influenced by higher-level processes. The net effect is that something moving or somehow changing is very difficult to ignore. Early pieces of instructional software would often repeatedly flash a word on the computer screen—literally to the point of distraction.

While examining real-time graphing on a perceptual level,
Brassell pointed out that movement in a computer display
can be used to direct student attention to the important parts
of a graph, where changes in the physical situation cause changes in the graph. VideoGraph, the project’s video
analysis software, was specifically designed to take advantage
of this attention-focusing mechanism. Although Cronin
and Cronin note that “few theorists have identified the
unique instructional advantages of IVI,” one can imagine
that being able to replay a video recreation of a motion event
while watching a synchronized graph would help students
make the cognitive link between the two.

II. SOFTWARE DESCRIPTION

The goal in designing the two software packages used by
students was to approach transparency—when the tool
seems to disappear and concentration is focused on the task
itself. The capture utility, VideoGrab, was probably most
successful in this respect. Students typically spent no more
than 5 min using it to digitize images they had captured on
videotape or located on a videodisc. Before the process was
automated, it was so difficult and time consuming that students
often did not have sufficient time to carefully examine
the physics depicted in their motion events. The analysis
program was much more complex in terms of user interface
issues. The considerations that went into the design of Video-
Graph have been described elsewhere.

Figure 1 is an example screen from the software. From
it, one can see that the central task of the package is to help
students link the motion event with its graph. Data represent-
ing the vertical position and velocity of the athlete’s center
of mass have been graphed. (The position of the center of
mass is calculated by the software once the locations of vari-
ous parts of the athlete’s body have been marked by the
student. This calculation assumes a typical distribution of
mass in the body.) The video window has been set up to
display several different objects at once. Notice also that the
video is indicating a series of markers for the objects being
displayed, showing object positions for all the frames in the
entire video sequence. Thus students have an easy mecha-
nism for viewing the complete path of each object, getting
around the limitation of a single video frame displaying ob-
jects at only one instant of time. The current position of the
object being graphed is surrounded by a bright circle on the
video. The display of multiple markers can be toggled on and
off so that users can view a single marker corresponding to
the particular frame actually being displayed at any given
time. Normally, this feature is turned on since students report
that it is quite helpful to be able to see where the object is
along its path.

With this software design students can examine the event
and its graph simultaneously rather than sequentially. The
brain’s working memory has a limited capacity and retention
time. The simultaneous presentation of event and graph
“makes the most” of the cognitive facilities available and
should make it easier to transfer the event-graph unit (now
linked together) into long-term memory as a single entity.
Perry and Obenauf suggest that this temporal alignment is
important to reasoning about motion. More generally, Shuell
notes that “Contiguity (the proximity of two events) is
well established as one of the fundamental variables affect-
ing traditional types of learning” (p. 426). According to
Fleming, “Side-by-side placement invites comparison. Crisi-
tial information is contrasted between the two, increasing
its saliency” (p. 245). Mayer and Anderson’s discussion of
dual coding theory observes that verbal and visual learning
are quite different. We might suspect that graphical representation of data has some aspects of verbal instruction since a sort of language is being used to present ideas in a concise manner. Certainly the video playback of motion events will involve visual learning. Utilizing these two modes simultaneously (in fact, synchronously) should be an effective means of instruction. In a study of students learning to calculate average speed, Back and Layne found that computer generated animations were more effective than still graphics, which were themselves better than text. Brungardt and Zollman did not see any effects on graphing skills when students analyzed four sports scenes, but expressed caution due to the small sample size of their study, noting that the probability of obtaining a statistically significant result was small. They did find that students were motivated by the exercise, were willing to discuss the motion events, displayed less confusion between velocity versus time and acceleration versus time graphs, and had a reduced tendency to attend to minor fluctuations in graphs. For this study, the VideoGraph software allowed students to compare videos directly with synchronized, animated graphs and to measure slopes and areas on the graphs. The expectation was that this would help them bridge the gap between the concrete visual display of a motion event and its abstract graphical representation. Also, a specially designed multiple choice graphing test, while not allowing the in-depth probing possible with interviews, did permit a large number of students to participate in the study.

The idea of providing a variety of ways to travel back and forth between visual and graphical representations has its foundation in Sternberg’s ideas of knowledge acquisition, three components of which are relevant here: (1) selective encoding—picking out relevant information for further processing, (2) selective combination—putting information together in a way which has meaning for the learner, and (3) selective comparison—noting relationships between new information and old information. Letting students select the technique(s) they prefer for linking video and graph should promote all three ways of acquiring knowledge. As noted earlier, we expect that the unusual parts of the graphs and motion events will draw the attention of the students. Since changes in motion are typically keys to understanding the causes of motion, the software takes advantage of students’ visual perception to direct them to exactly what they need to see to help them build their own (correct) ideas about kinematics and related graphs.

III. DESCRIPTION OF THE STUDY

A. Student populations

A group of teachers was contacted and invited to take part in the study. Each teacher was asked to incorporate video analysis into their curriculum as best they could, given their particular time and equipment constraints. What follows is a brief description of what was done by each.

Teacher A taught at a science magnet school, although not more than 40% of her students were classified as academically gifted. Even though all the high school students in the study were taking AP physics, about a third of her students did not have a calculus background. Approximately two thirds of her class sessions were exploratory laboratories where students were presented with situations to study, but were given minimal directions for conducting the investigation. Every three weeks students worked on a “creative lab” where they proposed something to study and presented their findings to the class. Her students became very proficient at using the video analysis and capture programs. The teacher said she would find it very difficult to go back to teaching kinematics without the video software. Occasionally students would combine sonic motion probes with video analysis. Most classes ended with students discussing whether their results were expected, if they were satisfied with the experience, what they would do differently next time, and, of course, what happened and why. The teacher said that her students used video to gain a better understanding of kinematics variables and the relationships between them and their connections to graphs. They explored questions like “Why would you want to use the slope of this graph to describe the motion?”. The teacher read over existing curricula such as Workshop Physics for ideas, but then developed her own lesson plans. Students used Graphs and Tracks, had a brief exposure to Interactive Physics, but were not using spreadsheets in class to any great extent. Groups of four or five students used video analysis to study a wide variety of situations, most of which they videotaped themselves. Using half a dozen computers brought into the classroom, they would look at basketball shots, high divers, soccer kicks, bungee jumping, springs, pucks on an air table, and rides at an amusement park. Images of additional sporting events were captured from videodisc. The classes were scheduled for two consecutive 45 min sessions, allowing sufficient time for in-depth student explorations. Teacher A had the opportunity to work with the video software for two academic years. The second year she added more situations for students to analyze and, in her estimation, instruction generally benefited from her experience with the materials.

Teacher B was the author of the software (and this paper) and so was probably able to take good advantage of the capabilities of the video analysis technique for demonstrations. No laboratories related to kinematics were taken by his college-level students prior to taking the graphing test, but video analysis demonstrations were used extensively. The technique was incorporated into approximately half the class meetings that dealt with kinematics. Highly student-involving discussions of the information presented by the software were conducted. Students turned in their predictions of what the graphs would look like before many of the situations were examined.

The other college classes were taught in large sections of traditional lectures. Smaller 110 min lab sessions were led by graduate teaching assistants (collectively labeled as “teacher C”). One group had their three regularly assigned non-MBL labs on velocity and acceleration, freefall, and oscillating springs replaced by three new labs that had students analyzing one- and two-dimensional motion and simple harmonic motion using the video software. They produced and videotaped their own motion events. No change in instruction was made other than guidance during the lab in the operation of the software and suggestions of what to look for on the software-generated graphs. Lab handouts asked students to study the relationships between the graphs and the videos, determine slopes and areas of the graphed curves, and compare the different graphs. The rest of the students’ labs did not incorporate video but were traditional kinematics activities, including rolling a ball off a ramp and measuring where it lands and a study of the rotational inertia of a disk.

Teacher D taught at the same science magnet high school.
as teacher A. His class sessions were single 45 min sessions so the labs his students worked on were more limited in scope. He used video analysis to a much lesser extent than did his colleague A or the graduate teaching assistants, C. Only two or three students carried out their own videotaping and image capture, and this was done outside of class for extra credit. Few students had taken calculus. Teacher D demonstrated the operation of VideoGraph in front of his classes, but did not review how to extract meaning from the graphs. Then student lab groups rotated through several lab experiences. Brief video analysis of one- and two-dimensional motion and momentum was supplemented with Sensei Physics tutorials and the use of a sonic ranger to determine the acceleration due to gravity. Additional nonvideo labs included timing freely falling water drops as another way to measure g, the monkey and hunter problem, and cutting a pendulum string and tracking the subsequent flight of the bob. Students were given short handouts to provide guidance through the labs. These were not "step by step" procedure lists, but mostly related the purpose of the assigned task and gave warnings about specific problems that might arise.

Teacher E taught at a suburban high school with limited computer resources. Kinematics instruction included demonstrations of motion graphs using an Apple II microcomputer and an ultrasonic rangefinder. This instruction, carried out in front of the whole class (of up to 30 students, most of whom had not had calculus) consisted of a series of cycles of prediction, demonstration, and discussion. The video software was utilized in a similar fashion, with students concentrating on the meanings of various graph sections and slopes. There was only one day of demonstration using VideoGraph since the computer equipment had to be borrowed. Hands-on lab work in kinematics was carried out using vibrating timers and paper tapes for analysis of free fall. A later lab used similar equipment to study an accelerating cart. All traditional instruction in kinematics and dynamics was completed before the use of the video analysis software.

Thus we have a sequence of decreasing incorporation of the video software into different kinematics curricula. Ranking these curriculum modifications from greatest to least, we have Table I.

### Table I. Scores on the Test of Understanding of Graphs—Kinematics for each type of classroom experience.

<table>
<thead>
<tr>
<th>Level</th>
<th>Classroom and laboratory experience</th>
<th>Teacher</th>
<th>N</th>
<th>TUG-K Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Very many video labs, second year of use</td>
<td>A</td>
<td>71</td>
<td>15.0±0.5</td>
</tr>
<tr>
<td>5</td>
<td>Many detailed video labs, first year of use</td>
<td>A</td>
<td>51</td>
<td>14.3±0.4</td>
</tr>
<tr>
<td>4</td>
<td>Very many extensive demos, no labs</td>
<td>B</td>
<td>13</td>
<td>12.9±0.8</td>
</tr>
<tr>
<td>3</td>
<td>Three detailed video labs + no video in lecture</td>
<td>C</td>
<td>14</td>
<td>12.1±1.1</td>
</tr>
<tr>
<td>2</td>
<td>Brief video labs + brief video demo</td>
<td>D</td>
<td>41</td>
<td>10.8±1.1</td>
</tr>
<tr>
<td>1</td>
<td>No video labs + extended video demo</td>
<td>E</td>
<td>88</td>
<td>9.8±0.6</td>
</tr>
<tr>
<td>0</td>
<td>No video analysis + no video labs</td>
<td>C&amp;E</td>
<td>90</td>
<td>10.1±0.5</td>
</tr>
</tbody>
</table>

**IV. ANALYSIS OF RESULTS**

The critical aspect of the data analysis is the labeling of the different levels of integration of video analysis into instruction. The grouping of student data into different "levels" was based on interviews with the teachers about what they had their students doing. Limited classroom observations were conducted to substantiate teacher reports. Level assignments were done before any data analysis was carried out so that the designation of levels would not be influenced by test scores. Other researchers familiar with the video analysis technique were also queried as to the appropriateness of the level designations. All agreed on the rankings presented here. Although this ordinal data enumeration establishes ranked variations in the amount of student use of video analysis in their kinematics labs, it implies no more than that. Although it is probably most strongly correlated with time on task, it certainly is not a linear measure based on timing data or some other mechanism for determining what students are engaged in. In other words, level 4 students did not necessarily work with video analysis twice as long as those in level 2. However, it can be said with confidence that level 4 students carried out more video analyses than those in level 2, with level 3 students' amount of video analysis somewhere in between.

Because of the practical difficulties of doing so, students were not randomly assigned to the different groups. The possibility of sampling from different schools biasing the results is not believed to be a problem here. Both teacher A and teacher D were from the same school and had access to similar students. Although the setting was a science magnet school, the majority of their students were not identified as gifted. In fact, teacher D's students did not do as well as those of the three instructors who make up the composite "teacher" C. During the development of the TUG-K (when none of the tested students at the magnet school were using video analysis) no significant differences in graph interpretation scores between that school and other schools across the country were noted ($t=1.12$, $df=167$, $p=0.13$).

That same test development project also indicated that, in general, high school and college student performances were identical ($t=1.50$, $df=522$, $p=0.13$). Thus we did not expect college students to score higher than their high school counterparts. In fact, their scores were right in the middle of the overall grade distribution for this study.

The effect of teacher bias and differences in the nonvideo portions of the curricula is more difficult to minimize. The problem was approached by having teachers C and E carry out both traditional instruction and some aspect of video analysis-based instruction. The only difference between C's level 3 students and the students of teacher C in the control
Table II. An analysis of variance indicates that the different levels of video analysis made a significant impact on kinematics graph interpretation scores. "Between groups" refers to the variation in graphing test scores resulting from differences in the mean test scores for the different levels of video integration. "Within groups" is the amount of score variation between students within the individual levels, i.e., the unsystematic error due to all remaining uncontrolled differences between students. The MS or mean square values are calculated by dividing the sum of squared variances of scores from the mean \( SS = \sum_{i=1}^{n} (x_i - \bar{x})^2 \), by the appropriate number of degrees of freedom, \( df \). The \( F \) statistic is given by \( MS_{between\,\,groups} / MS_{within\,\,groups} \). In other words, it is the ratio of controlled score variation to uncontrolled variation. The \( P \) value calculated here is the probability that the between group score variation would be nearly 14 times larger than the within group variation in a random set of data. It is essentially zero, so it is highly unlikely that the wide variation in mean TUG-K scores between the different levels was due to chance.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between groups</td>
<td>1721</td>
<td>6</td>
<td>286.9</td>
<td>13.92</td>
<td>3E-14</td>
</tr>
<tr>
<td>Within groups</td>
<td>7442</td>
<td>361</td>
<td>20.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9164</td>
<td>367</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Although the ANOVA results indicate a significant upward trend in test scores as level of video integration increased, it was especially important to discern the impact of video demonstrations alone. (Many schools with teacher workstations in the classroom cannot afford student computers. This would allow video analysis in a demonstration setting only.) The application of unequal variances \( t \) test indicated that there was no difference between level 0, with no use of video analysis, and level 1, where there was a single demonstration of the software \( (t=0.42, \, df=171, \, p=0.64) \). This finding is consistent with the generally held notion that hands-on experience is more effective than lecturing. However, many extensive demonstrations presented over extended periods of time and specifically structured to involve students in predicting and comparing graphs (level 4) did have an impact, although they were not as effective as a mixture of many hands-on labs and demonstrations (levels 5 and 6).

The analysis clearly indicates that the richer the curriculum, the more students will learn. These data are consistent with the findings of the earlier video analysis study where only one motion event was analyzed. Apparently having students analyze a single event did not provide sufficient experience to make an impact. The weakest speculation that can be made from these new data is that video analysis, when combined with other microcomputer-based lab and simulation experiences, definitely helps students learn to interpret kinematics graphs. However, I believe a stronger conclusion is possible. The same part of the design concerned with teacher bias (by having C and E work with both control and video groups) also shows that simply replacing several traditional labs with video-based ones can make a difference, even if none of the other labs are MLBs or simulations. Students working with teacher C and carrying out the three video-based labs performed significantly better than C's students who worked with traditional labs \( (t=3.4, \, df=57, \, p<0.01) \). No other aspect of their instruction was changed. The strongest inference one might make from the data is that video analysis by itself made all the differences between groups. The correct conclusion is probably somewhere between the two extremes. In any case, it is fair to say that video analysis is a pedagogically valuable addition to the introductory physics curriculum. The technique works in a variety of situations and with different teachers but does not appear to be effective when used solely for brief lecture demonstrations.

V. DISCUSSION AND IMPLICATIONS FOR INSTRUCTION

The data indicate quite strongly that the variation in TUG-K scores between groups is significantly larger than the variation within each group. If our designation of levels is valid we can conclude that the differences in graph interpretation scores can be attributed to the varying amount of video analysis for each group. This result is perhaps more easily seen in Fig. 2, illustrating that graphs can be a more meaningful way to display numerical results.

![Fig. 2. Kinematics graph interpretation ability as a function of the amount of integration of video data analysis into instruction. The first two TUG-K scores are not significantly different.](image)

VI. CONCLUSION

Developing instructional software is an intellectually challenging, time consuming task. Application of research in physics education, combined with input from the field of human perception, can result in computer-based materials that students find exciting to use and helps them learn complex material. But how that software is used in the classroom makes a tremendous difference in its educational impact. It is probably true for all instructional technology, not just VideoGraph, that teachers must thoroughly integrate software into their instruction and not just tack it on. They must supply a variety of ways for students to become involved with the content, essentially establishing an environment for learning. The more hands-on experience and mentally engaging tasks we can present to our students, the better they will grasp the
material. In this type of setting, video analysis tools can help students develop an understanding of kinematics graphs, a fundamental part of introductory physics.

ACKNOWLEDGMENTS

This work was supported by NSF Grant No. MDR-9154127 with additional support from the RasterOps Corporation, Sony Corporation of America, and Apple Computer, Inc. Thanks also to the teachers who opened up their classrooms for research and to the members of the Physics Education Research Group at North Carolina State University for their helpful insights.